Baseband Feedback Frequency-Division Multiplexing with Low-Power dc-SQUIDs and Digital Electronics for TES X-Ray Microcalorimeter

K. Sakai, Y. Takei, R. Yamamoto, N.Y. Yamasaki, K. Mitsuda (ISAS/JAXA)
M. Hidaka, S. Nagasawa, S.Kohjiro (AIST),
and T. Miyazaki (RIKEN)

sakai@astro.isas.jaxa.jp

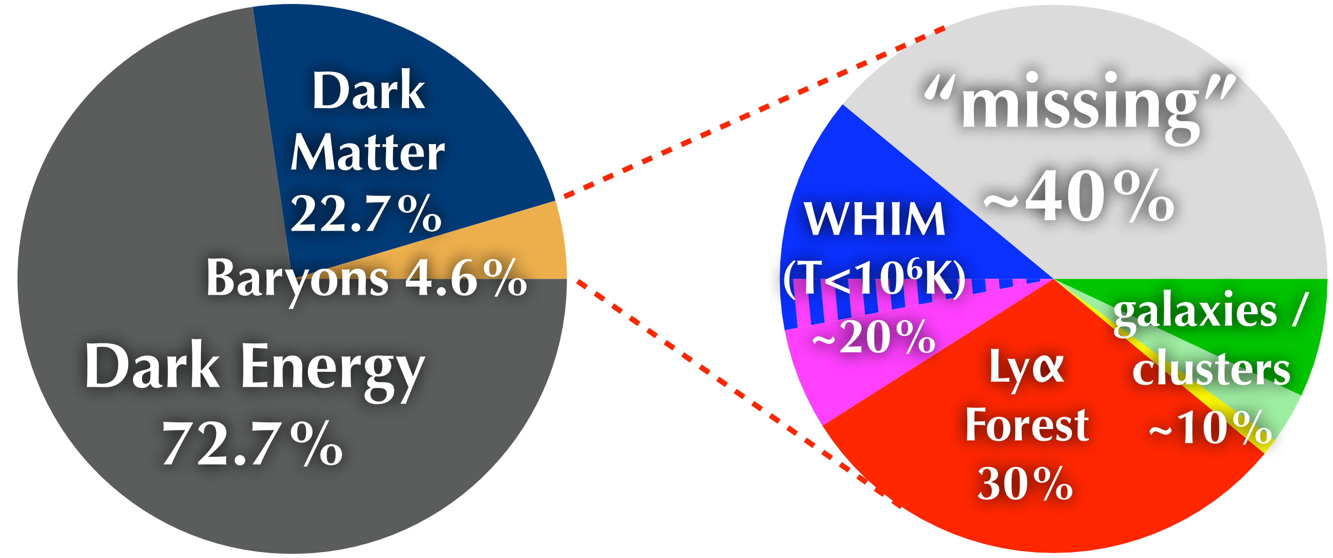
National Institute of Advanced Industrial Science and Technology
AIST

RIKEN

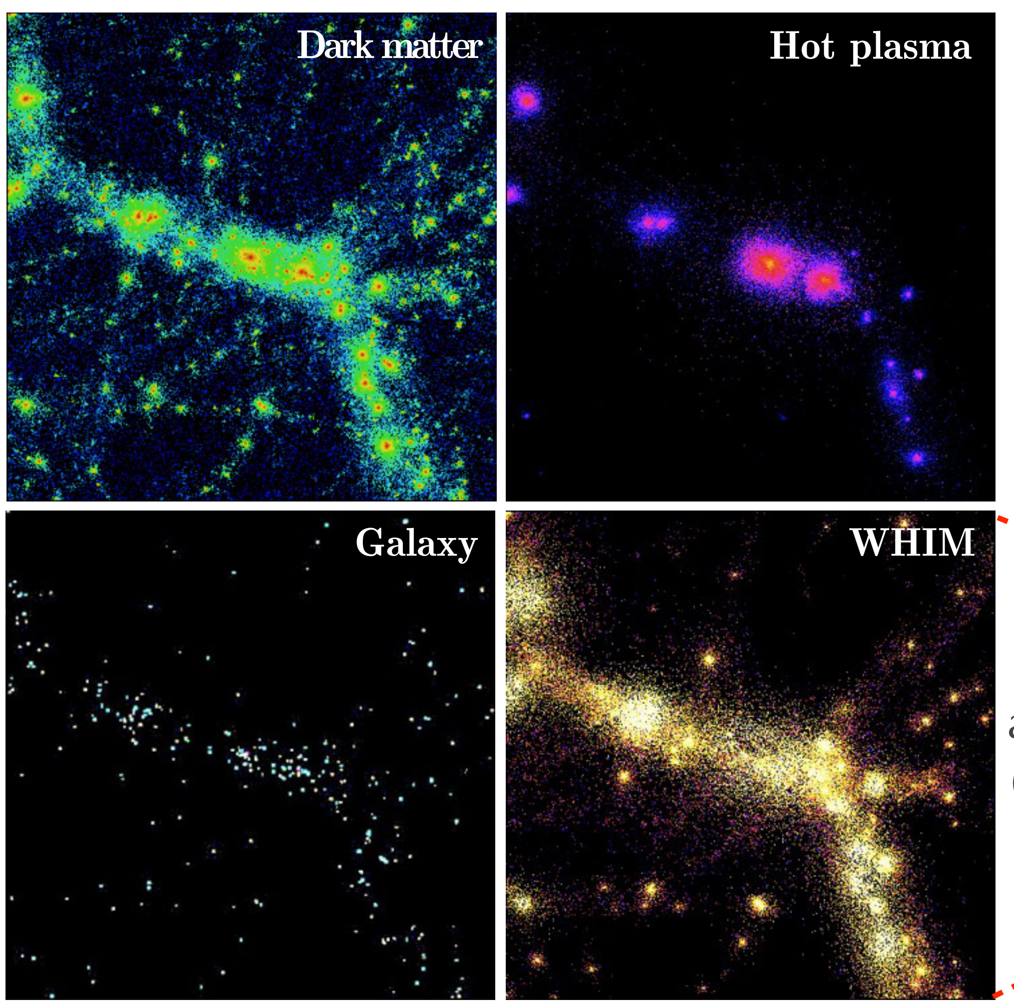
JAXA
Japan Aerospace Exploration Agency

Missing Baryon Problem and DIOS Satellite Mission

- ✓ The Universe contains only 4.9% ordinary matter
- ✓ About a half of the baryons in the local Universe are *not* observed



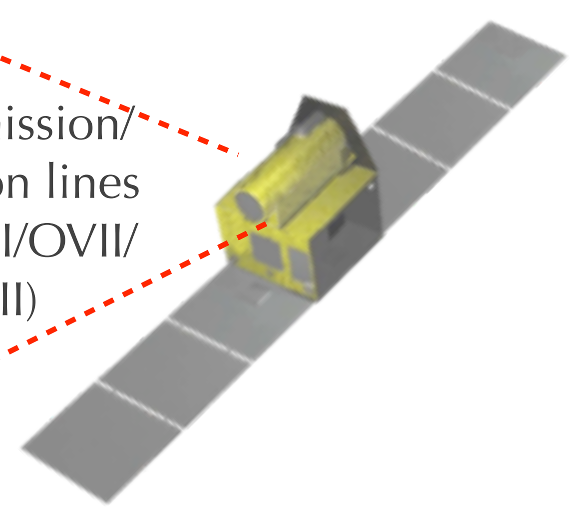
Compiled by M. Shull

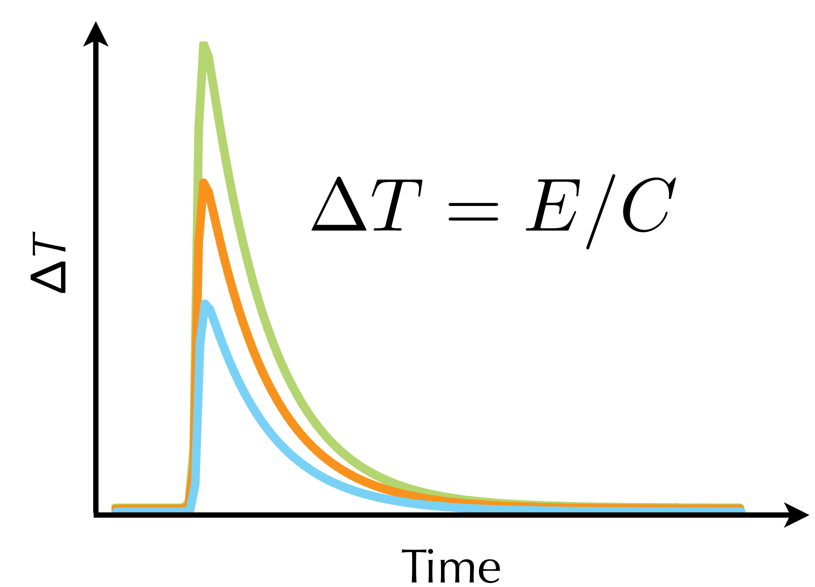


Yoshikawa et al. 2001

- ✓ Warm-Hot Intergalactic Medium ($T > 10^6$K) is the best candidate
- ✓ DIOS (Diffuse Ionized Oxygen Surveyor)
- ✓ High-resolution spectroscopy using 16x16 (or more) TES array

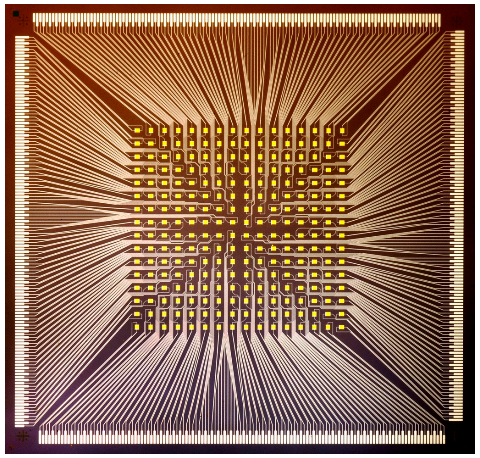
X-ray emission/ absorption lines (e.g., OVI/OVII/ OVIII)





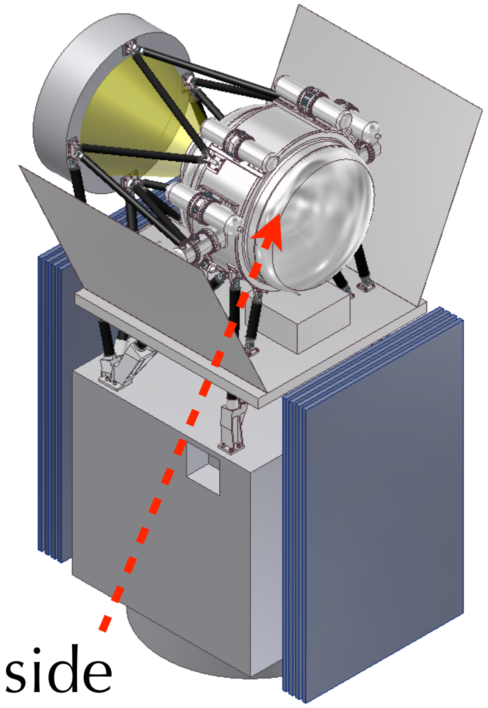
Requirements of DIOS Mission

TES



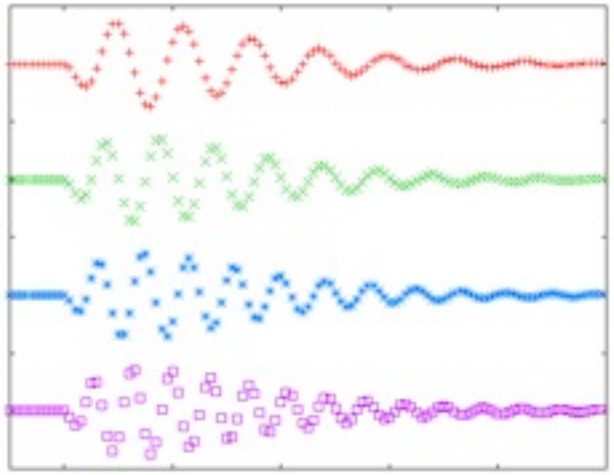
- ✓ > 256 Channel for WHIM mapping
- ✓ Radiation tolerant
- ✓ See Poster 411 (Yamada+ on Thu) and Poster 409 (Ishisaki+ on Thu)

Refrigerator (ADR)



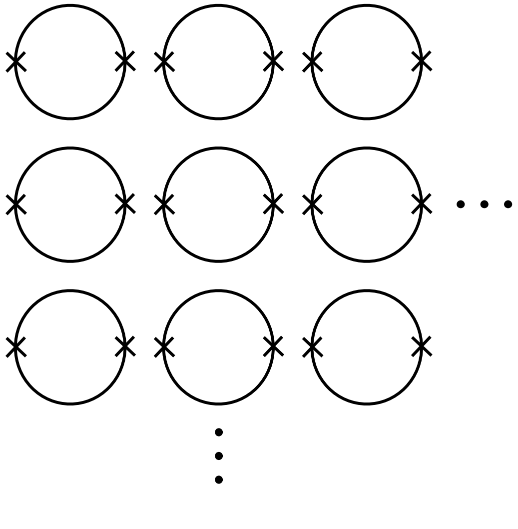
- ✓ Equiv. to Astro-H ADR
- ✓ ~ 640 nW@50 mK
- ✓ See Poster 402 (Hishi+ on Fri)

Readout



- ✓ BBFB FDM
- ✓ > 8 Mux
- ✓ Digital electronics

SQUIDs



- ✓ < 20 nW/SQUID
- ✓ Multi-input SQUID for FDM
- ✓ Radiation tolerant

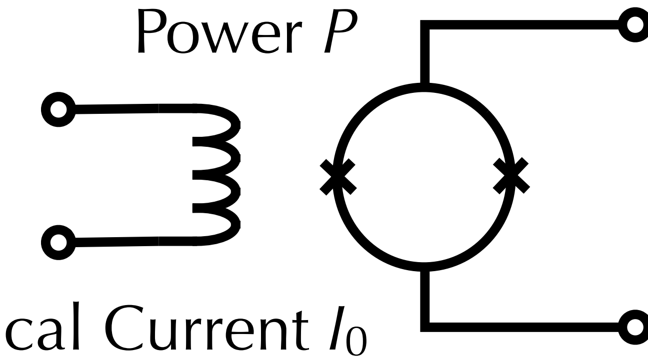
This talk

Requirements to SQUIDs

Power P

Equivalent Input Current Noise I_N

Input Coil Self-Inductance L_{in}



Transimpedance Gain Z_{tran}

Dynamic Resistance R_{dyn}

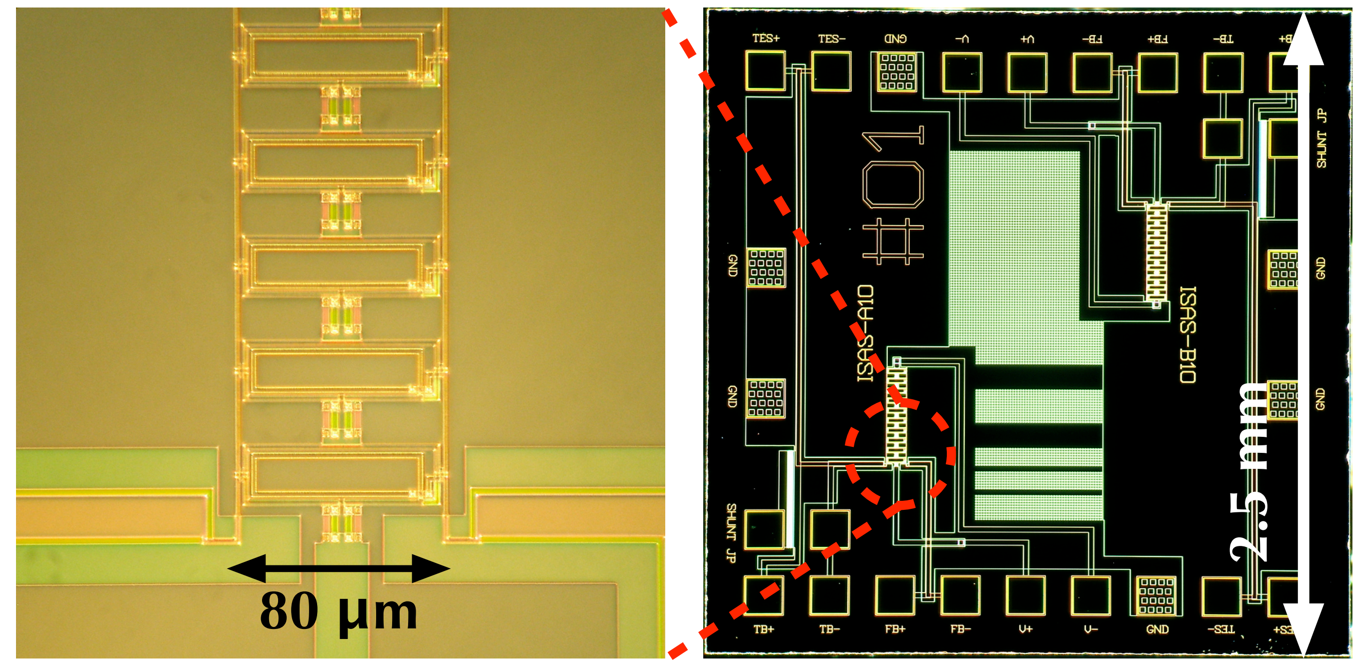
Critical Current I_0

		Goal	Required	Conventional SQUID	I_0 Dep
Power P	nW	< 20	< 32	100	$\propto I_0^2$
Transimpedance Gain Z_{tran}	Ω	> 100	> 80	220	$\propto I_0$
Gain per unit Power Z_{tran}/P	Ω/nW	> 5	> 2.5	2.2	$\propto I_0^{-1}$
Equiv Input Current Noise (@4.2K) I_N	pA/√Hz	< 10	< 20	1.3	$\propto I_0^{-1}$
Input Coil Self-Inductance L_{in}	nH	< 1	< 2	6.2	-
Dynamic Resistance R_{dyn}	Ω	~ 50	< 100	600	-

- ✓ Smaller critical current for smaller power, but smaller gain
- ✓ Maximize the gain per unit power
- ✓ Make I_0 smaller within the noise allowance limits

Performance Measurement Results

- ✓ Designed by JAXA, fabricated in CRAVITY@AIST
- ✓ I_0 is set to 10 μA (process-recommended minimum)
- ✓ All requirements are met
- ✓ **Gain per unit power is now x2 more** while **power is 80% less**

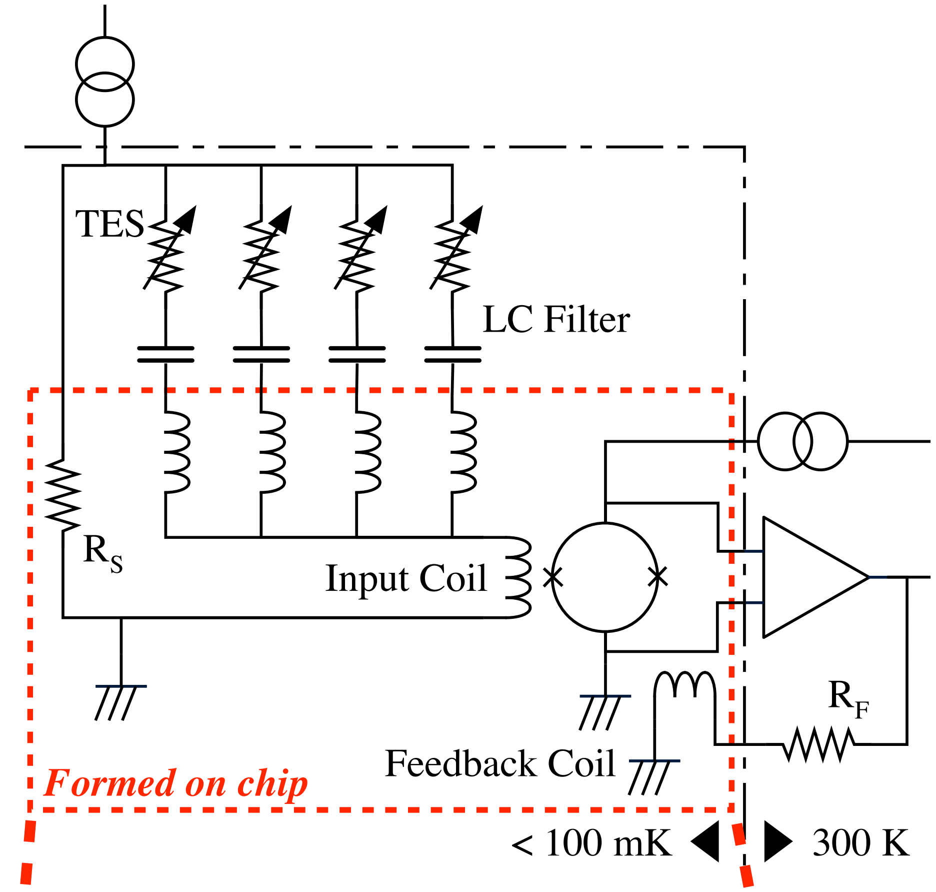


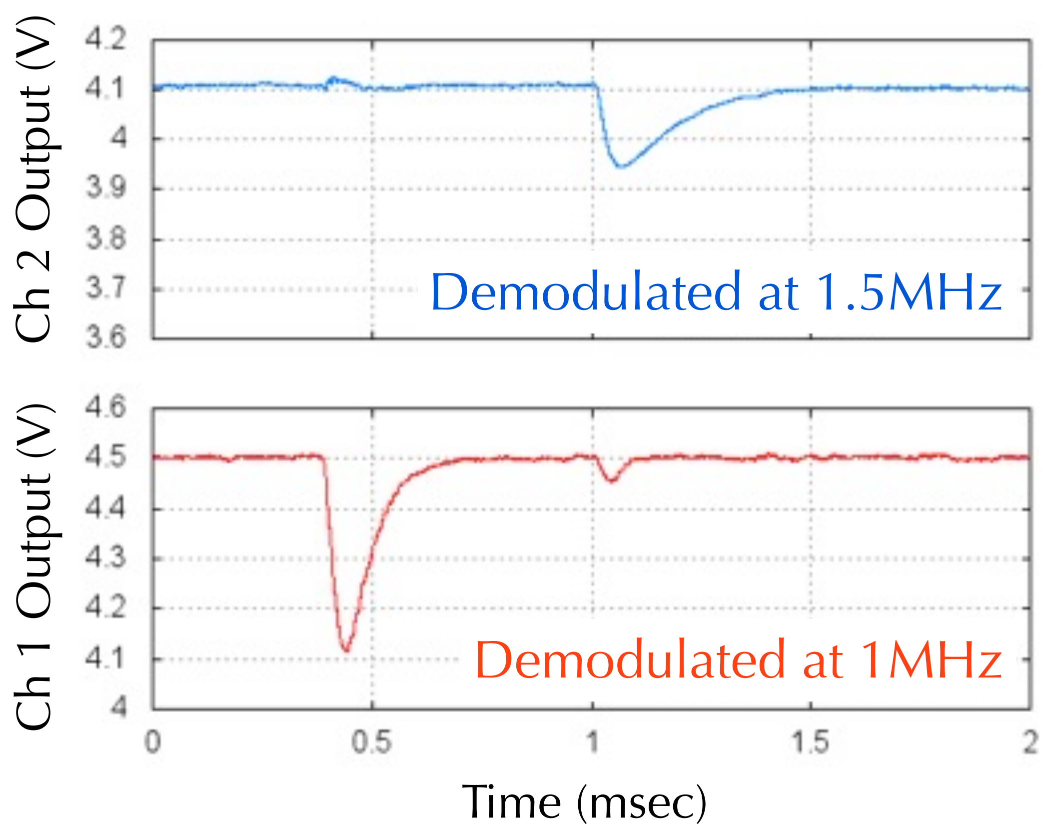
Low-power SQUID

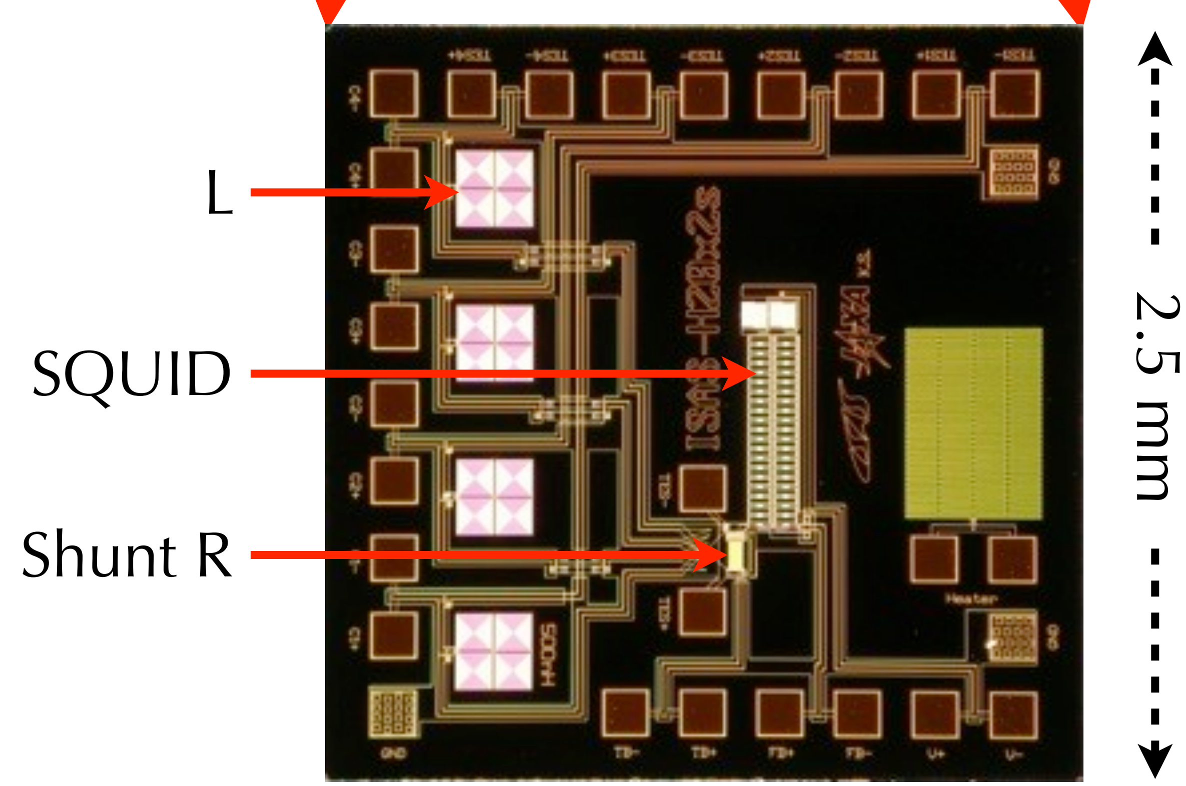
		Goal	Required	New	Conventional SQUID	
Critical Current I_0	μA	-	-	**10**	15	**30%** ↓
Power P	nW	< 20	< 32	**21**	100	**80%** ↓
Transimpedance Gain Z_{tran}	Ω	> 100	> 80	**87**	220	**60%** ↓
Gain per unit Power Z_{tran}/P	Ω/nW	> 5	> 2.5	**4.4**	2.2	**×2**
Equiv Input Current Noise (@4.2K) I_N	pA/√Hz	< 10	< 20	**8**	1.3	**×6**
Input Coil Self-Inductance L_{in}	nH	< 1	< 2	**1.3**	6.2	**80%** ↓
Dynamic Resistance R_{dyn}	Ω	~ 50	< 100	**96**	600	**85%** ↓

Development of 4-input SQUID Chip for FDM

- ✓ 2.5 mm-square chip with 1 SQUID, 1 shunt resistor (5 mΩ), and 4 inductances (~500 nH) for LC filters
- ✓ Capacitors are externally attached
- ✓ Current-summing multiplexing
- ✓ Successfully multiplexed 2 TES signals (1.0 and 1.5 MHz) with BBFB analog electronics
- ✓ See Poster 503 (Yamamoto+ on Tue)

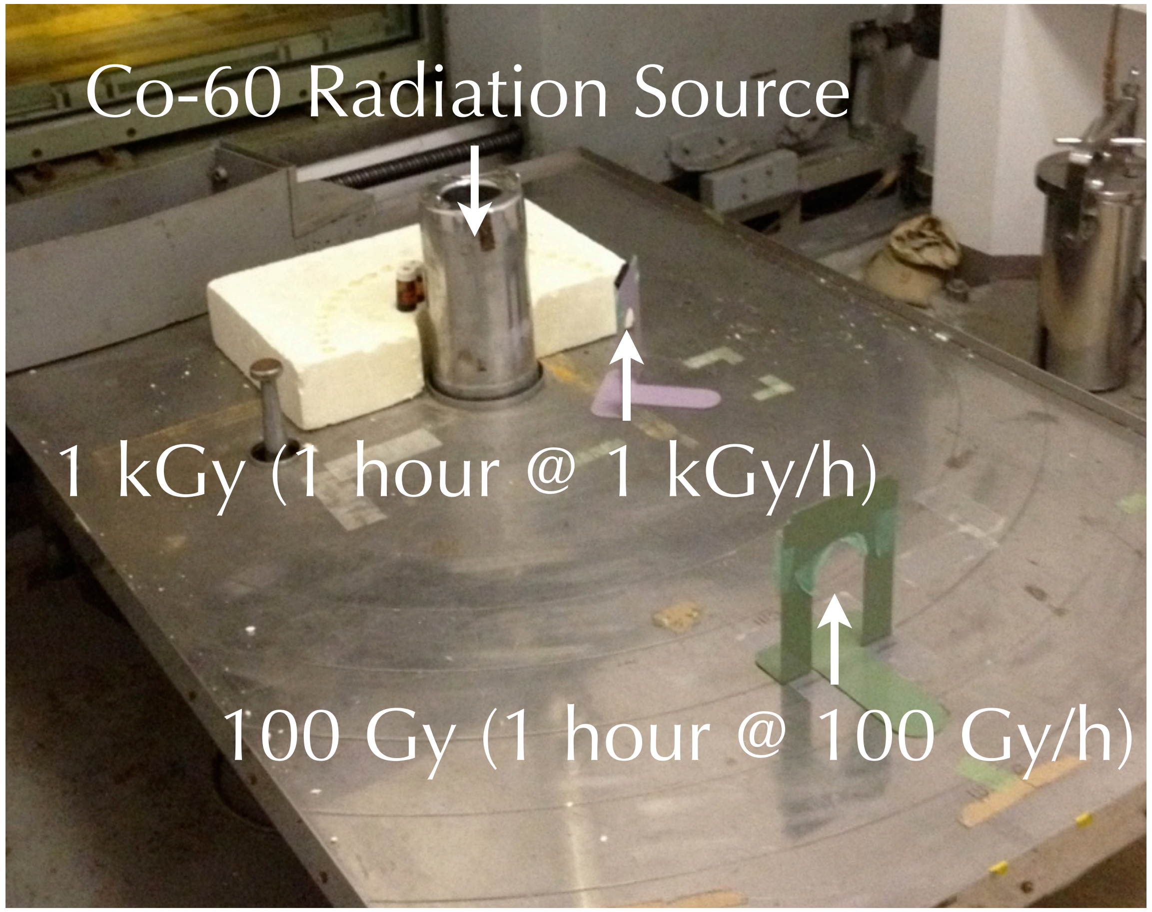


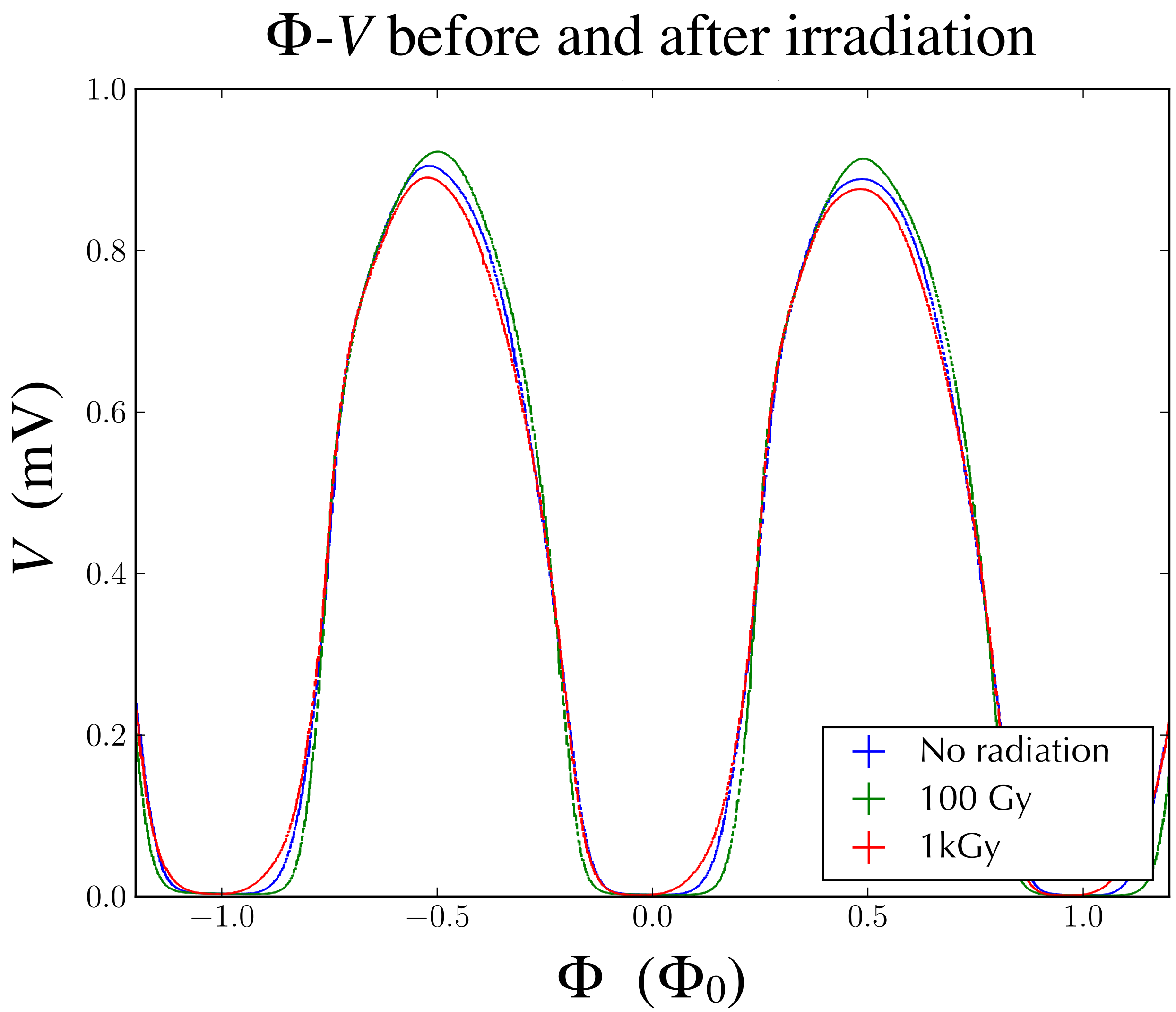




Radiation Tolerance Evaluation using Cobalt-60

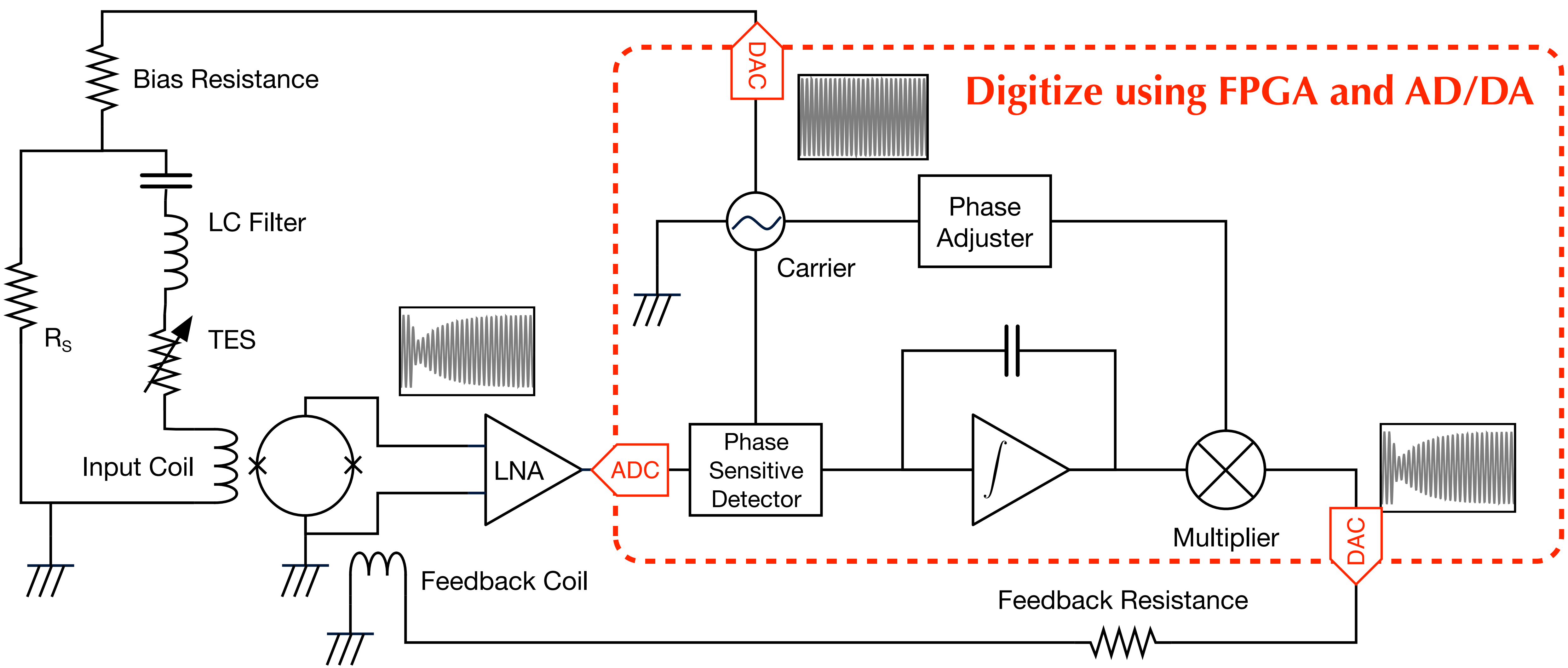
- ✓ Junctions may be damaged by cosmic radiation
- ✓ Radiation tolerance evaluated using Co-60 (@Tokyo Institute of Technology Radioisotope Research Center)
- ✓ Irradiation dose of equiv to 50 yrs in low Earth orbit with 1 mm Al shield (1 kGy)
- ✓ **No significant change** before and after irradiation
- ✓ See Poster 409 (Ishisaki+ on Thu) for TES radiation tolerance evaluation





Digital Electronics for Baseband Feedback FDM Readout

- ✓ BBFB basics: signals (~10 kHz) from TES is sent back to SQUID after carrier (~1 MHz) phase has been adjusted
- ✓ Digitize existing analogue electronics using FPGA and ADC/DAC for more flexibility and less lead time
- ✓ Digital electronics is compact, low-power, and easy to scale



Requirements for Implementation

ADC and DAC

- ✓ ADC/DAC Sampling rate ≫ Carrier frequencies
- ✓ ADC Sampling resolution ~ Resolving power
- ✓ DAC Sampling resolution ~ Resolving power × Number of ch

FPGA

- ✓ Sufficient number of multipliers

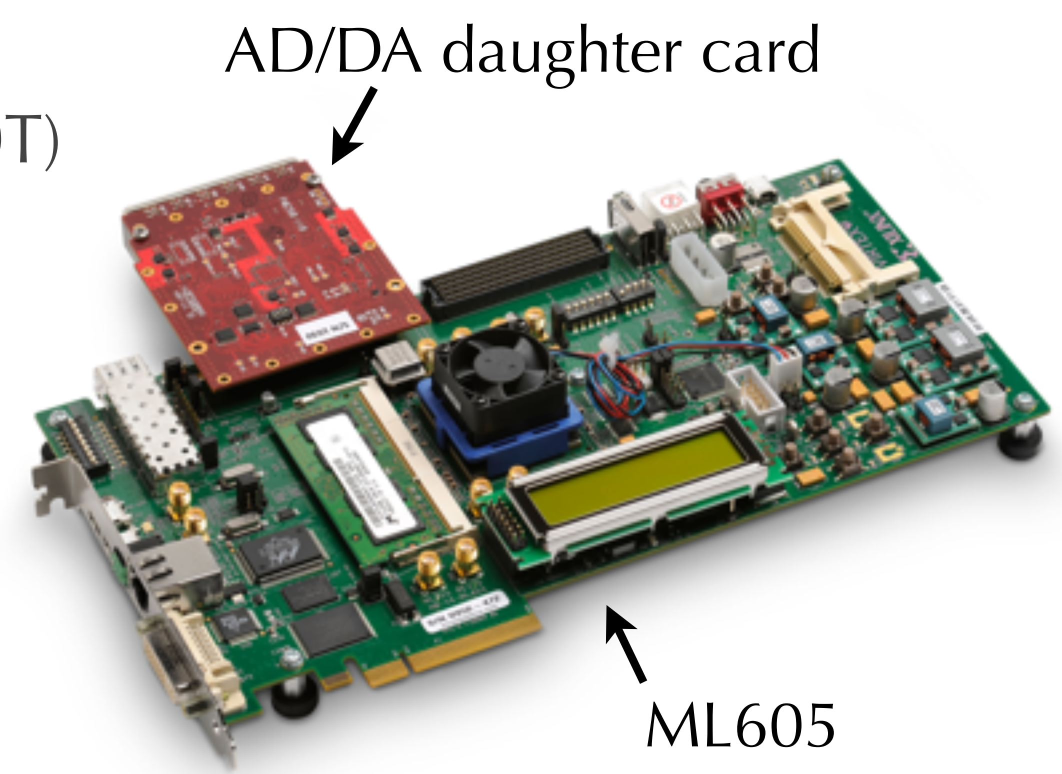
Virtex-6 FPGA DSP Kit with AD/DA

FPGA: Xilinx ML605 Eval Board (Virtex-6 LX240T)

- ✓ Logic Cell: 240k (LUT: 960k, FF: 1920k)
- ✓ Multiplier: 768 (25-bit × 18-bit)
- ✓ Block RAM: 15Mb

AD/DA: 4DSP FMC150

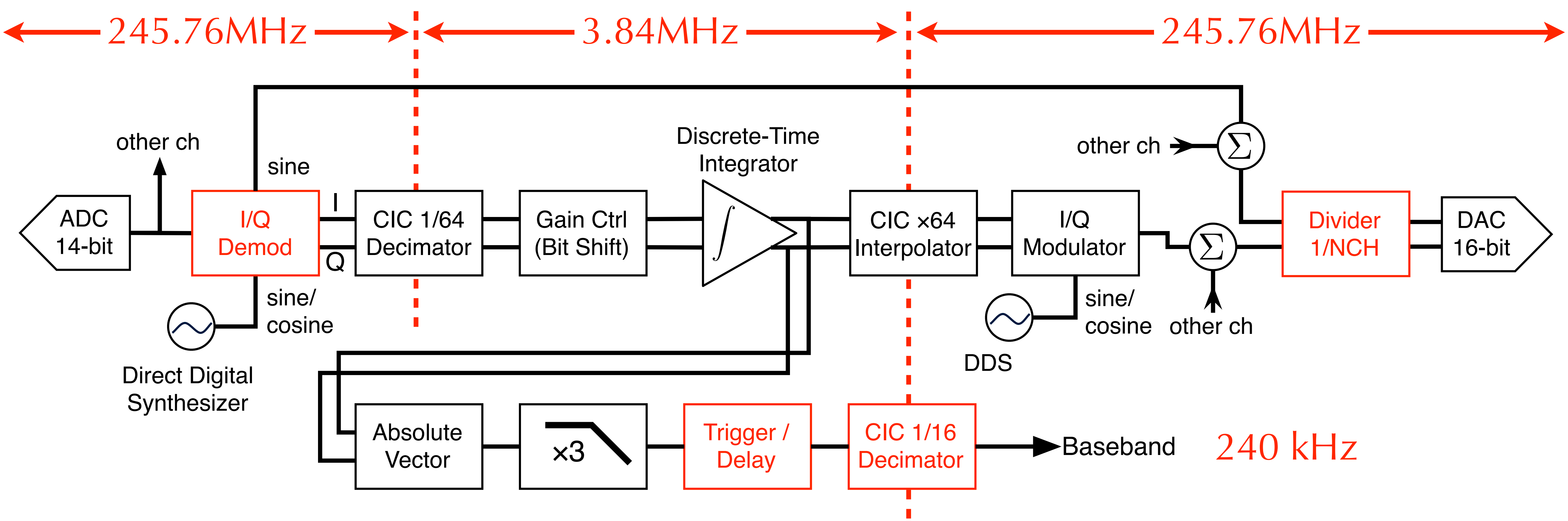
- ✓ ADC: Dual-channel 250MSPS 14-bit ADC
- ✓ DAC: Dual-channel 800MSPS 16-bit DAC



* Kintex-7 FPGA DSP Kit should also work fine

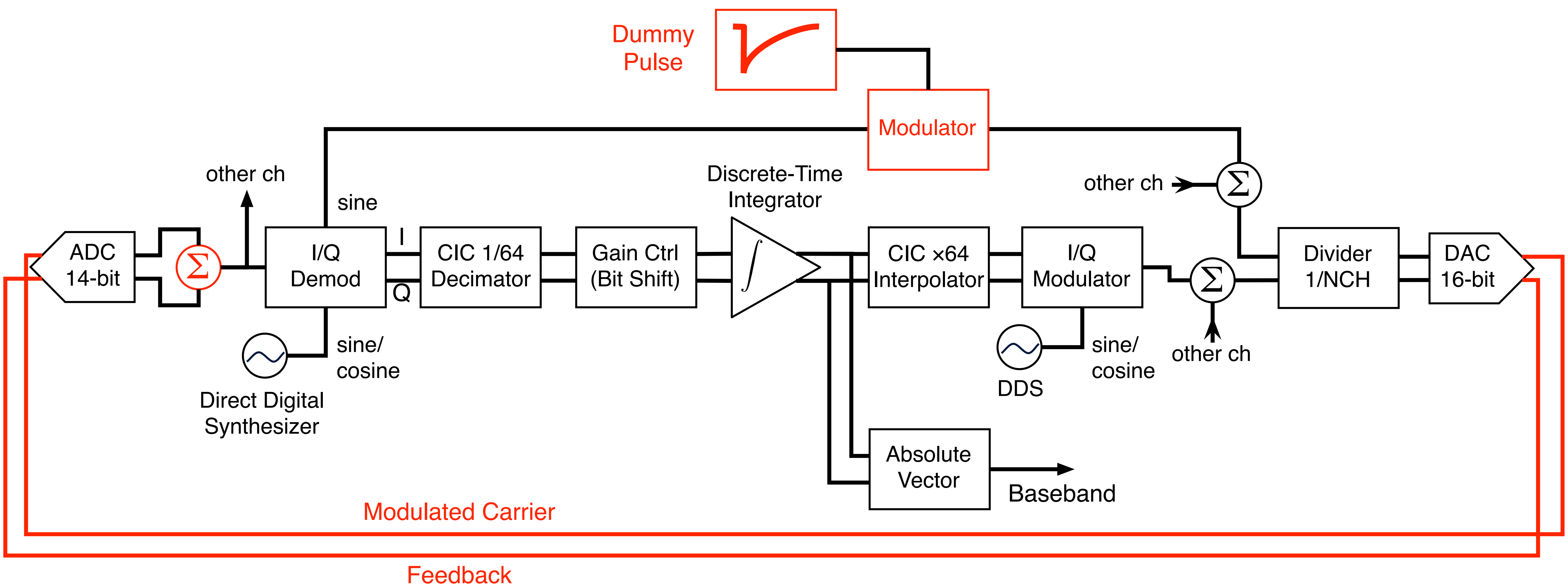
Digital BBFB Design

- ✓ Use I/Q Modulator/Demodulator instead of PSD for stable demodulation
- ✓ Carriers and feedbacks of all channels are summed then divided by the number of channels (NCH)
- ✓ 245.76 MSPS for ADC and DAC
- ✓ 3.84 MHz intermediate frequency to suppress trigger jitter
- ✓ 240 kHz baseband frequency for smaller data rate



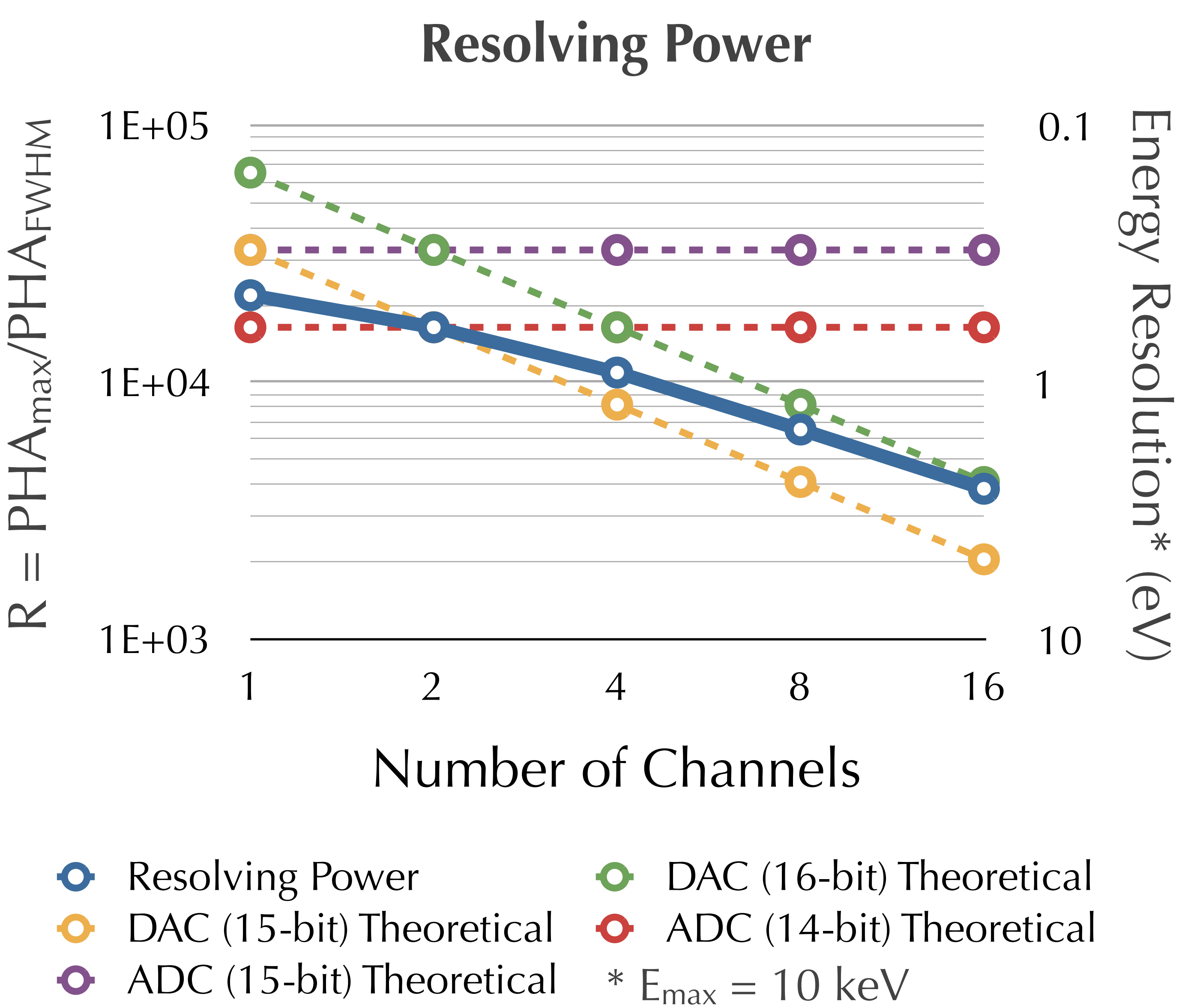
Evaluation of Signal-to-Noise Ratio

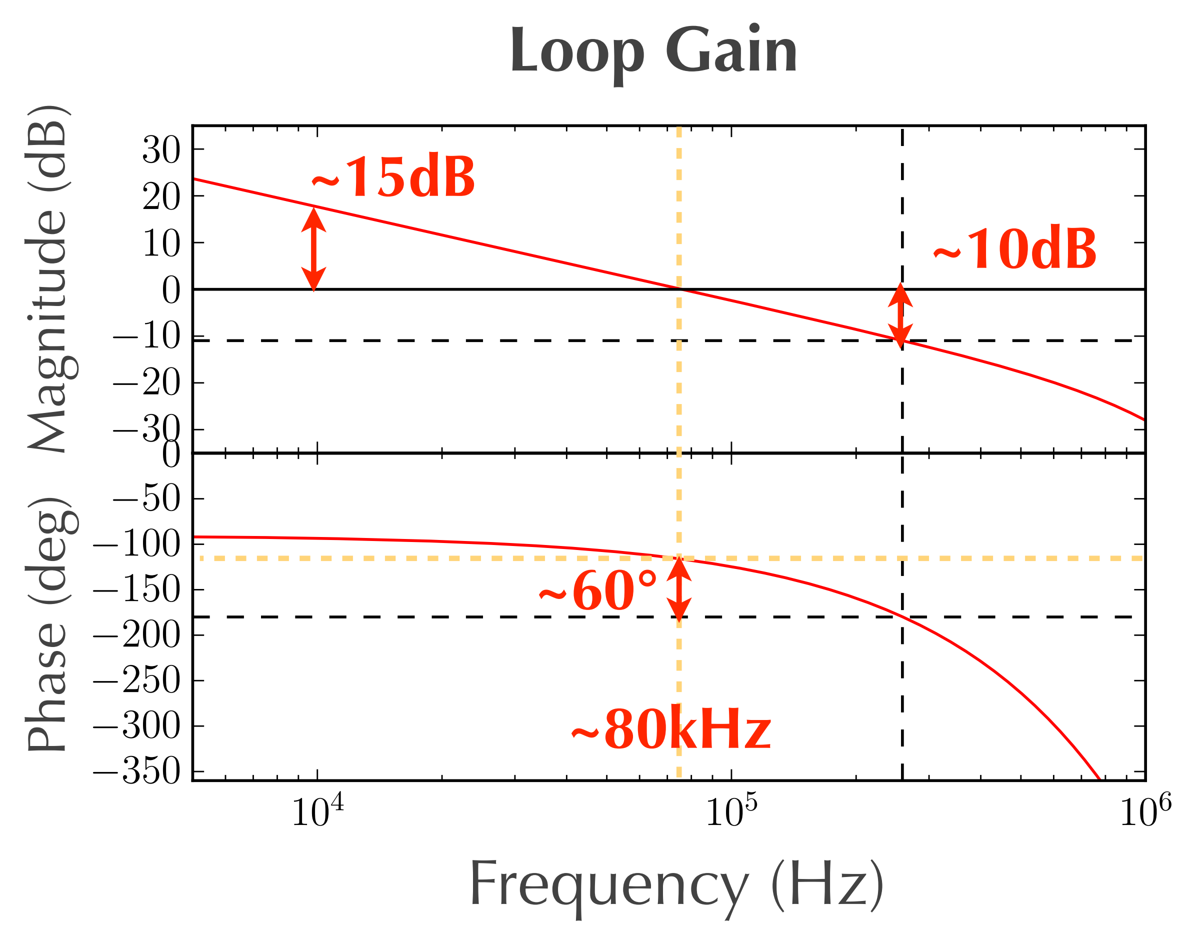
- ✓ Evaluate SNR in *loopback mode* up to 16-ch
- ✓ TES bias and Feedback are digitally summed
- ✓ TES bias for the target channel is modulated by dummy pulse (2 ms, 80% modulation) while other channels are not modulated
- ✓ Carrier frequencies 5 to 7 MHz with 128 kHz spacing
- ✓ Optimal Filtering with ~16,000 2-ms noises/pulses
- ✓ Calculate resolving power R (=PHA_{max}/PHA_{FWHM})



Resolving Power and Loop Gain

- ✓ R ~ 7000 for 8-ch, and R ~ 4000 for 16-ch
- ✓ Resolving power is limited by ADC resolution for NCH < 2, and by DAC resolution for NCH > 2
- ✓ Open-loop gain of ~15 dB@10 kHz with phase margin of ~60° and gain margin of ~10 dB





Summary

SQUID

- ✓ Developed low-power and FDM-optimized SQUID
- ✓ All requirements for SQUID are met
- ✓ Developed 4-input SQUID Chip for FDM
- ✓ No significant change before and after irradiation

Digital Electronics

- ✓ Developed digital BBFB FDM readout system
- ✓ Resolving power of ~4000 in 16-ch multiplexing
- ✓ Open-loop gain of ~15 dB @ 10 kHz

Future

- ✓ Develop low-power SQUIDs with more gain
- ✓ TES readout using digital electronics